Evaluation of Elements Affecting the Effectiveness of Maintenance Policies Following the ASME Code and Delay Time Model

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Abstract

Root cause analysis of two years breakdown data of a Beverage Company in Nigeria reviews that man and method are the predominant cause of failures in a production system. This further relates to the competence of maintenance personnel. This study adopts a method based on the implementation of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI Appendix VIII) (Boiler and Committee, 1962) integrated to a delay time model to analyze and predict the expected downtime from different technicians based on capability. As a large series of tests was not feasible, a smaller "weed out" 8/10 test was designed using binomial power curves to determine the probability of perfect inspection (PPI). Numerical analysis shows that as the competence of a technician drops, there is a disproportionate increase in the proportion of downtime. For a given cycle of 24 hours, when an inspection is been carried out by a technician with a probability of detection (POD) of 0.8, the expected downtime is 1.8 hours. When this activity is performed by another with a POD of 0.65, the expected downtime is 4.2 hours. There is about a 56% increase in the proportion of downtime compared with the corresponding 24% difference in POD score.

Keywords
Maintenance, Maintenance Policy, Root Cause Analysis, ASME Code, Delay Time Model

1. Introduction
In theory, maintenance management could have benefited from the advent of this large area of operations research known as maintenance optimization modelling. A maintenance optimization model is essentially a mathematical model that quantifies both the costs and benefits of maintenance and finds the best balance between the two while accounting for all types of constraints.
Generally, maintenance optimization models address four issues:

i. description of a technical system, its function, and its significance,
ii. modelling of the system's deterioration over time and possible consequences for the system,
iii. description of the available information about the system and the management actions, and
iv. an objective function and an optimization technique that aids in finding the best balance.

In literature, a large number of maintenance optimization models are developed and thus, the following questions arise. First and foremost, what is the value of maintenance optimization models in terms of maintenance management? How frequently and in what context have these models been successfully applied? For the few adopted strategies, why do they not give the expected result as production systems that have benefited from the models are still being threatened by a large amount of unplanned downtime from breakdown. These questions are mostly considered as a pitfall on the usefulness of optimization models, research into an organization maintenance system reviewed that in reality, there is a gap in understanding of the impact of maintenance optimization variables on the actual result expected from optimization models. Some of the variables are greatly influenced by the maintenance personnel carrying out the maintenance activity.
This work aims to model the predominant elements affecting the effective application of maintenance policies based on the root cause of failure analysis and evaluate the impact on the output of the production system in terms of downtime proportion.

2. Literature Review

The ability to predict critical failures that may lead to long downtime is a key factor in reducing the overall cost along the supply chain (Lin et al. 2013). Any breakdown that occurs during production will lead to a disruption in the supply chain, hence the need for adequate maintenance (Ascher and Feingold 1984; Fiondella et al. 2015). Maintenance is a continuous process and demands continuous improvement to achieve the desired efficiency and effectiveness at a minimal cost (Berrade et al., 2017; EMC Corporation, 2015). In theory, maintenance management could have benefited from the advent of this large area of operations research known as maintenance optimization modelling. A maintenance optimization model is essentially a mathematical model that quantifies both the costs and benefits of maintenance and finds the best balance between the two while accounting for all types of constraints. The selection of the best approach to sustaining a particular asset has been quite a challenge for the asset owner and study has shown that companies experience a gap between the potential and realised benefits of advanced maintenance methods and techniques (Grubic and Jennions, 2018; Tiddens, 2018). Nelson- Aalen's nonparametric reliability estimator was utilized to estimate the reliability function of slurry pumps using historical failure data for analysis (Barberá et al., 2014). Monte Carlo simulation was to determine the expected frequency of lightning strikes on the equipment and the equipment damage probability were ascertained (Necci et al., 2013). Lin and Chang (2013) worked on the application of network analysis in the measurement of production systems performance (Lin and Chang, 2013). Traditional method of failure analysis which entails backtracking using fault tree and other methods of fault diagnosis to determine the root cause of failure (Mathias et al., 2016). The logic gate simulation approach in determining the availability and reliability of a system with mixed series-parallel configurations (Reni et al., 2014). Yang and Aldemir (2016) proposed a backtracking algorithm in the form of a search tree which recursively enumerates all the sub-trees of an undesirable event and traverses the different paths from the top event of concern by branching (J. Yang and Aldemir, 2016). Janssens et al. (2016) focused on the use of mathematical programming models and a meta-heuristic approach that uses a greedy random adaptive search procedure to find an initial solution and tabu search to improve it (Janssens et al., 2016). A modified Weibull distribution is referred to as the addictive modified Weibull (AMW) distribution which is very flexible in modelling the bathtub-shaped hazard rate data and adapts to the sharp change of the hazard rate in the initial and ware-out phase was proposed by (He et al., 2016). Zhong et al. (2014) modelled a dynamic classifier based on a statistical model referred to as the dynamic latent classification model (DLCM); a combination of a naive Bayes model and a mixture of factor analysers. The model is designed for the analysis and classification of streaming data (Zhong et al., 2014). Barberá et al. (2014) applied a graphical analysis method for maintenance management is used to support maintenance decision-making through visualization and graphical analysis of data (Barberá et al., 2014). According to Kulak and Kahraman (2005), in making production decisions such as maintenance, a number of variables are considered (Kulak and Kahraman, 2005). Maintenance strategy, maintenance personnel skills and experience, human resources and availability of spare parts are some variables on which maintenance decision is based (Adebiyi et al., 2004; Löfsten, 2000; Swanson, 2001). These variables have the conditions of certainty and uncertainty, particularly in a dynamic environment (Hojati, 2004) .

Boiler and Committee (1962) adopts a method based on the implementation of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI Appendix VIII) (Boiler and Committee, 1962) integrated to a delay time model. Performance Demonstration Initiative (PDI) is the primary administrator for the ASME Code Section XI Appendix VIII blind qualification tests for ultrasonic inspectors in the United States. As direct measurements are impossible, indirect measurements in the laboratory were used to estimate the probability of detection for inspectors in a laboratory environment, followed by a planned assessment of the differences between laboratory and field examinations(Cumblidge and D'Agostino, 2016).

This Appendix VIII qualification is unique in that it needs to be repeated and passed every three years to maintain the qualification. It is worth noting that Appendix VIII was primarily designed as a screening tool to weed out ineffective procedures, equipment, and personnel, and was not designed to provide a precise measure of the POD for the inspectors. With an established system (equipment and procedure) personnel were required to be certified by their employers (Doctor et al., 2013). The employer certification involved organized training to become familiar with the principles and practices of a specific test method. Written examinations (covering both general principles and specific applications) and a practical hands-on examination were also required for Level I and II personnel. Written examinations covering the Basic, Method, and Specific areas of knowledge were required for Level III personnel (ASME, 2019).

Naiara et al (2017) propose a multi-criteria model for a pavement inspection policy, using Delay Time Modelling, to establish the optimal period of inspections at an airport in the Northeast of Brazil, focusing on cost and availability (Naiara et al., 2017). An inspection and replacement policy for a single component system that successively executes missions with random durations was studied in (L. Yang et al., 2016) using delay time-based maintenance models. Aven and Castro (2009) considered the basic delay-time model in which a system has three states, the perfect functioning state, a defective state and the failure state (Aven and Castro, 2009). Wang (2011) consider the joint optimisation of three decision variables namely; the ordering quantity, ordering interval and inspection interval using the Delay-Time concept where the objective function is the long-run expected cost per unit time in terms of the three decision variables to be optimised (Wang, 2011). For a system that is comprised of many components and subject to many different failure modes, one of the most convenient ways to model the inspection and failure processes is to use a stochastic point process for defect arrivals and a common delay time distribution for the duration between defect the arrival and failure of all defects (Wang et al., 2010). The building of the decision model was to establish inspection intervals of condition monitoring based on delay time analysis assumptions and a multi-criteria framework. Wang et al. (2014) introduce a two-level inspection policy model for a single component plant system based on a three-stage failure process characterized by the delay-time concept (Wang et al., 2014). Such a failure process divides the system's life into three stages: good, minor defective and severe defective stages (Driessen et al., 2017). Wang (1997), worked on the problems of obtaining a subjective estimate of the delay time distribution used in maintenance modelling are discussed (Wang, 1997). Models for combining experts' opinions and updating the delay time distribution were also discussed. Berrade et al. (2017) and Oosterom et al.(2014) applied the delay time model (DTM) to determine the optimal maintenance policy under an assumption of postponed replacement (Berrade et al., 2017; Oosterom et al., 2014). Lopes et al (2015) pointed out why the application of inspection policy is important, failure management is also essential (Lopes et al., 2015).
Despite the hundreds of literature and models being developed, its usage in the industry, especially in developing countries, is very thin. Many maintenance models are stochastic, which is not only difficult for technicians and managers to understand, but also difficult to interpret. Thus, there is a disarray in alignment with the expected benefits from maintenance strategies and attained performance. To reduce machine downtime, it is imperative to have a detailed understanding of the different factors that contribute to machines' unavailability and how their impact could be tracked, analysed and reduced to increase productivity.

3. Method

3.1 Skill Audit Design Based on ASME Code Section XI Appendix VIII Standard

The goals of the Appendix VIII tests are to ensure that technicians with an unacceptable probability of detection would have a low probability of perfect inspection while skilled technicians should have a good probability of perfect inspection. The ideal way to do this would be to have each technician look at a large series of specimens to evaluate the technician's probability of detection (POD) for a series of flaw sizes to precisely measure each inspector's skill. This approach is, unfortunately, prohibitively expensive and time-consuming. The binomial distribution is frequently used to model the number of successes in a sample of size drawn with replacement from a global population. As a large series of tests was not feasible, a binomial experiment is conducted. The probability of getting exactly k successes in M independent Bernoulli trials is given by the probability mass function (PMF) in Equation 1

$$PMF = \binom{M}{k} POD^{k}(1 - POD)^{M-k} \tag{1}$$

Where:
PMF = Probability mass function
POD = Inspector Probability of Detection
M = Total number of units inspected
k =Total number of successes
$\binom{M}{k}$= binomial coefficient which can be represented in the form of Equation 2

$$\binom{M}{k} = \left(\frac{M!}{k!\,(M-k)!}\right) \tag{2}$$

As a large series of tests was not feasible, a smaller "weed out" test was designed using binomial power curves to determine the probability of perfect inspection as in Equation 3

$$PPI = \sum_{k=C_1}^{M} \binom{M}{k} POD^{k}(1 - POD)^{M-k} \tag{3}$$

3.2 Integrating competency into delay time model for measuring downtime

The delay time model was modified according to prevailing scenarios to account for the dependency of inspection and maintenance quality on technical competence. The delay time model has the following assumptions.

i. The ability to identify a defect during an inspection is determined by the competence of the maintenance technicians expressed by the probability of perfect inspection (PPI)
ii. The average time to repair a breakdown is subject to the technician's capability
iii. When the competency of the technician is at the expert range i.e $PPI = 1$, a perfect inspection is expected.

Let the time of arrival of defect be y, after an initial inspection point O as shown in Figure 1.

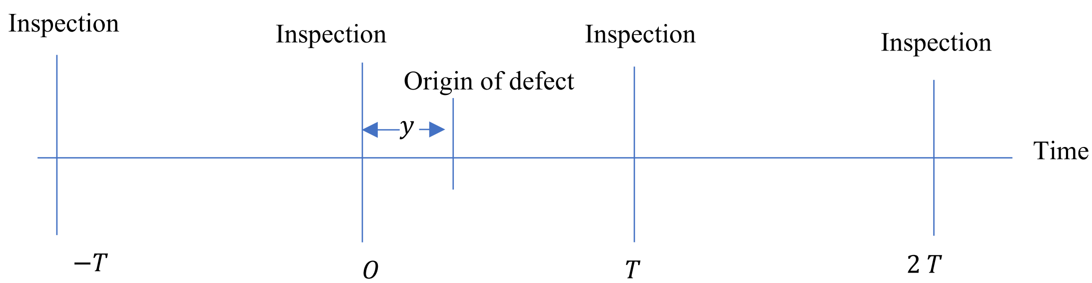

Figure 1. Defect distribution

The defect could be identified at an inspection T without causing a breakdown if the delay time $t > (T - y)$ or at $2T$ if $t > (2T - y)$ and so on, provided that the minimum delay time t of defect is long enough. Assuming a technician with a given probability of perfect inspection (PPI), the probability of defect be identified during an inspection is expressed as

$$Prob\ of\ \ defect\ identified\ at\ T = PPI\ \times prob\ (no\ breakdown\ before\ T) \tag{4}$$

$$Prob\ of\ defect\ identified\ at\ T = \times\ R(T - y) \tag{5}$$

$R(T - y)$ is the probability that a defect arriving at y will not result in a breakdown before T.
If the defect was not identified at time T, then the probability of it being identified during the next inspection $2T$ is given by Equation 6

$$Prob\ of\ defect\ identified\ at\ 2T = PPI(1 - PPI)R(2\,T - y) \tag{6}$$

The probability that a defect initiated at point y will be identified at an inspection $n\,T$ is given by Equation 7

$$Prob\ of\ defect\ identified\ at\ nT = PPI(1 - PPI)^{n-1}R(n\,T - y) \tag{7}$$

In general, the probability that a defect initiated at point y will be identified at any given inspection is given by equation 8

$$Prob\ of\ defect\ identified\ \ = \sum_{n=1}^{\infty} PPI(1 - PPI)^{n-1}R(\,n\,T - y) \tag{8}$$

Summing over all possible y, which is uniformly distributed over T, we have for the probability that a defect arises as a breakdown $b(R)$ under this scenario be given by Equation 9

$$b(R) = 1 - \left\{ \int_{y=0}^{T} \sum_{n=1}^{\infty} \frac{PPI}{T} (1 - PPI)^{n-1} R(\,n\,T - y)\,dy \right\} \tag{9}$$

The probability of fault not resulting in a breakdown is expressed as

$$R(t) = 1 - F(t) \tag{10}$$

where

$$F(t) = \int_{0}^{T} f(t)dt \tag{11}$$

$f(t)dt$ is the probability of fault arising within a period (O, T) has a delay time within $(t, t + dt)$. Assuming the probability density function $f(t)$ of delay time has been chosen as a negative exponential distribution as expressed in Equation 12 and the cumulative density function $F(t)$ expressed in Equation 13

$$f(t) = \alpha e^{-\alpha t} \tag{12}$$

$$F(t) = (1 - e^{-\alpha t}) \tag{13}$$

The probability of fault not resulting in a breakdown given s defect arrival rate of α is given as

$$R(t) = 1 - (1 - e^{-\alpha t}) \tag{14}$$

By substituting Equation 14 into Equation 9, the probability that a defect arises as a breakdown $b(R)$for all possible y, uniformly distributed over T is given by Equation 15

$$b(R) = 1 - \left\{ \int_{y=0}^{T} \sum_{n=1}^{\infty} \frac{PPI}{T} (1 - PPI)^{n-1} \{1 - (1 - e^{-\alpha(nT-y)})\} \, dy \right\} \tag{15}$$

Integrating Equation 15 we have

$$b(R) = 1 - \frac{PPI}{\alpha T} \sum_{n=1}^{\infty} \{(1 - PPI)^{n-1} e^{-\alpha nT} (e^{-\alpha T} - 1)\} \tag{16}$$

$$b(R) = 1 - \frac{PPI}{\alpha T} (-e^{-\alpha T} - 1) \sum_{n=1}^{\infty} \{(1 - PPI)^{n-1} e^{-\alpha nT}\} \tag{17}$$

Further simplifying equation 17 we have the probability that a defect arises as a breakdown as

$$b(R) = 1 - \frac{PPI(1 - e^{-\alpha T})}{\alpha T\{1 - (1 - PPI)e^{-\alpha T}\}} \tag{18}$$

From the estimate of $b(R)$, if the average downtime for breakdown repair is d_b, the expected downtime $D(T)$ per unit time to be incurred given that fault arrived independently at a constant rate k while operating an inspection policy of period T is given in Equation 19

$$D(T) = \frac{[\, kTd_b^c b(R) + d]}{T + d} \tag{19}$$

The average time to repair a breakdown d_b is dependent on the skill of the technician assuming that spare parts and tools are available. With this factor into consideration, breakdown repair time d_b^c for a given technician is expressed in Equation 20

$$d_b^c = d_b + (1 - PPI)d_b \tag{20}$$

Substituting Equation 20 into Equation 19 the expected downtime $D(T)$ per unit time will be is given as

$$D(T) = \frac{[\, kT\{d_b + (1 - PPI)d_b\}b(R) + d]}{T + d} \tag{21}$$

Substituting the probability that a defect arises as a breakdown represented by Equation 18 into the downtime Equation 21, the downtime equation $D(T)$ is thus Expressed as

$$D(T) = \frac{kT\left[\{d_b + (1 - PPI)d_b\}\left[1 - \frac{PPI(1 - e^{-\alpha T})}{\alpha T\{1 - (1 - PPI)e^{-\alpha T}\}}\right]\right] + d}{T + d} \tag{22}$$

4. Data Collection and Presentation

The packaging line of Nigerian Breweries plc was understudied for a period of three years (2019 to 2021). Packaging is the process of putting beer/malt into a package. The line data software was used in collecting all performance data including breakdowns and minor stoppages. The focus of this work is on stoppage up to 30 minutes. Breakdown in this category is selected for detailed root cause analysis using the Five Why method. The list of the analysed breakdown in 2019 to 2021 are presented in Table 1

Table 1. Summary of analyzed breakdown data

4M	Downtime (minutes)	Count of 4M
Machine	267	5
Man	5262	36
Man/Machine	80	1
Material	92	2
Method	4061	47

4.1 Skill Audit with ASME Design

To evaluate the skill level of the maintenance technicians, calibration templates were designed according to the particular maintenance function requirement to determine the probability of fault detection (POD). Table 2 show a calibration form for a mechatronics technician to test electrical skills.

Table 2. Technician performance demonstration test

MECHATRONICS CALIBRATION EVALUATION					
	Date:	**18/11/2020**			
	AUDITOR'S NAME:	Christian Okonta			
	TECHNICIAN'S NAME:	Jude Eze			
	CHECKPOINT	Very OK = 4	Just OK = 3	Partially ok = 1	Not ok = 0
A	**SAFETY**				
1	Open a Panel and ask the technician to identify all non-basic condition items		1		
2	Ask the technician to identify the LOTO point on the Panel	1			
3	Check if the technician is carrying out a task and see if he is using the right tool. Ask technician which tool he requires to carry out a particular task if the technician is not currently carrying out a task		1		
	Subtotal	1	2	0	0
B	**AUTOMATION EQUIPMENT MAINTENANCE**				
	ELECTRICAL STANDARD				
4	Can a mechatronics technician be able to use a multimeter to check for voltage, Current and continuity measurement in any electrical components in a panel	1			
5	Ask the technician to identify all components in a Panel - Use different Panels for a technician to reduce the tendency of them getting info from those who have already done		1		
6	Ask the technician to explain the function of any component you chose		1		
7	Can a mechatronics technician be able to identify electrical components using the electrical diagram		1		
8	Pick a cable/component and ask the technician to check what it is connected to	1			
9	Can technician tell and then check what voltage levels are expected at any point you may choose	1			
10	Can a mechatronics technician be able to trace an open circuit and short circuit fault? Let him explain what he needs to do and how he will do it		1		
	Subtotal	3	4	0	0
	PLC				
11	Identify a field device and let the technician trace its connection from the field to the PLC	1			

	CHECKPOINT	Very OK = 4	Just OK = 3	Partially ok = 1	Not ok = 0
12	Can a mechatronics technician be able to identify all the PLC individual modules of a machine	1			
13	Can mechatronics technicians be able to open an S7 program to view a machine program		1		
14	Can a mechatronics technician be able to identify all the PLC modules of a machine		1		
15	Can the technicians identify ET modules and the difference		1		
16	Can the technician tell what kind of signal can be connected to what type of module		1		
	Subtotal	2	4	0	0
	INSTRUMENTATION				
17	Can mechatronics technician be able to identify the process control loop e.g filler level control, wort cooling temperature control etc - The components and the function within the loop		1		
18	Can the technician explain what signal (and signal value) is expected at any point in the loop which you choose		1		
19	Can the technician identify the I/P converter or conversion point in the loop		1		
20	Can the technician identify any modulating valve and explain its operations	1			
21	Can technician identify a solenoid valve on the line and explain its operation and connection to the place where he has identified it	1			
	Subtotal	2	3	0	0
	GENERAL				
22	Can a mechatronics technician be able to check and confirm if an electric motor is burnt? He should demonstrate using a motor and confirm his real understanding by asking other probing question	1			
23	can mechatronics technician be able to know the action to be taken when replacing frequency drive for an electric motor		1		
24	Has the technician been participating in PM or Breakdown resolution? Ask probing questions. E.g how did you solve the last breakdown - analyse the answer. OR what do you do in maintenance	1			
	Subtotal	2	1	0	0
	STRUCTURED FAULT FINDINGS				
25	Can mechatronics technicians be able to carry out simple fault finding on the machine (simulate a fault and see how the technician approach it)? If not possible to simulate you can ask any theoretically on-site and let him explain and point to and possibly show you the tools	1			
	Subtotal	1		0	0
	Total Score	11	14	0	0
	Weighted score	44	42	0	0
	POD score	**0.86**			

5. Results and Discussion

5.1 Graphical Results of Breakdown Data

Graphical analysis of the data in Table 1. illustrating the contribution of man, method, machine and material (4M) to the number of breakdowns experienced with the observed period is shown in Figures 2.

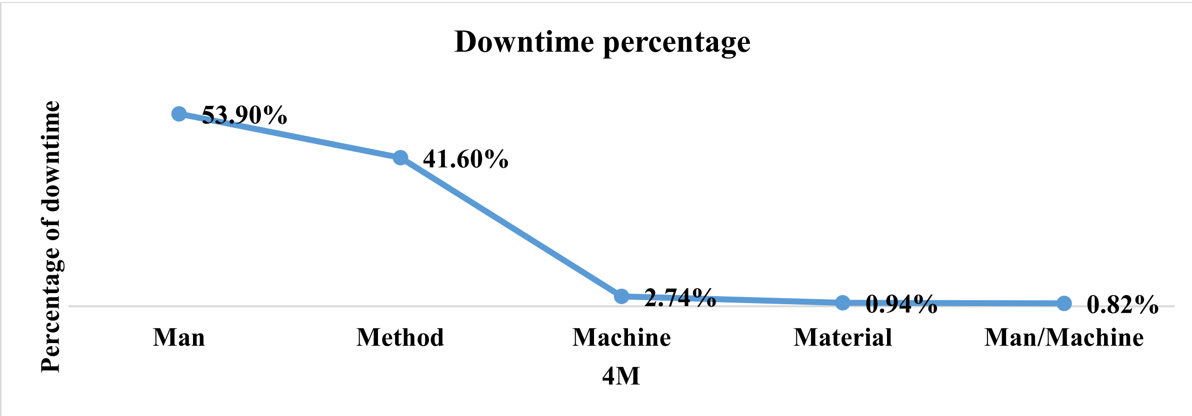

Figure 1. Percentage of downtime and their corresponding 4M root cause

5.2 ASME Code Audit Result

Using the power curve equation in Equation 3., Figure 3 shows a plot of a four standard ASME test for evaluating the probability of perfect inspection (PPI) from the performance demonstration test. The tests must give a technician with a low POD a very low chance of perfect inspection. The 5/5 test is significantly more difficult than a 14/20 test, but it was decided during the design of Appendix VIII that a 4/5 test would allow poor inspectors through too often.

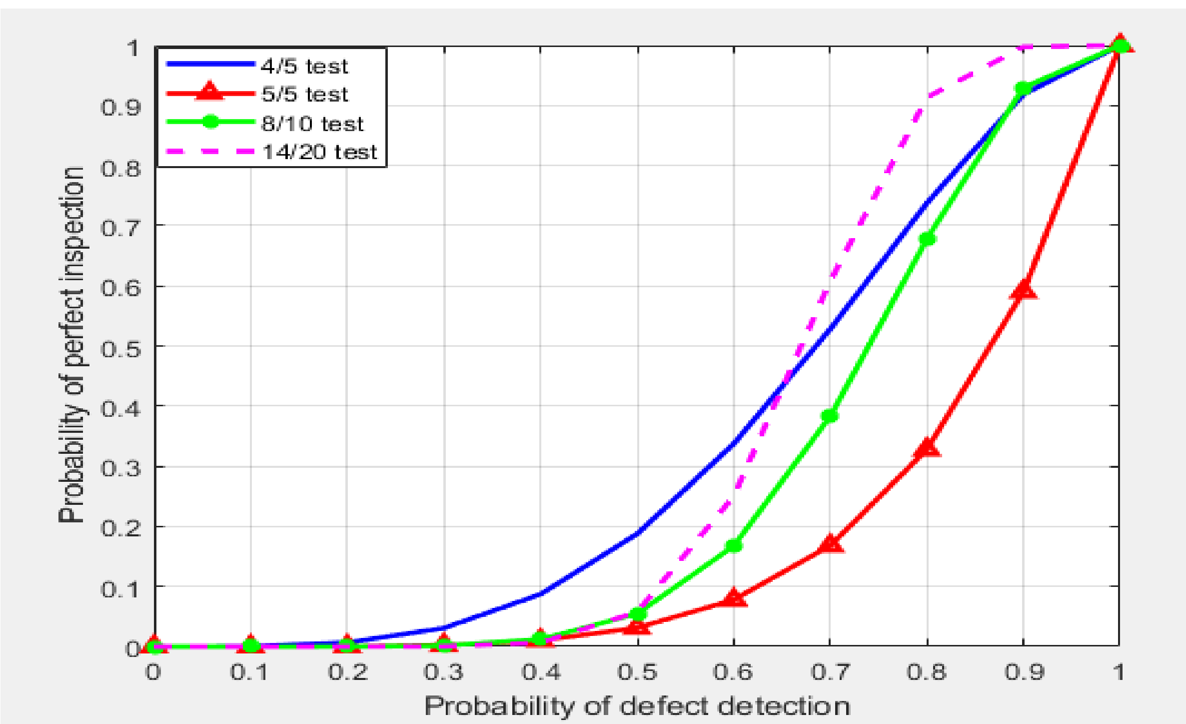

Figure 2. Example Power Curves

The 8/10 test was chosen because it is a "medium" difficulty test as a technician is required to at least have an intermediate level skillsets for proper maintenance execution and the result of skill evaluation is shown in Table 3.

Table 3. Skill audit score

Candidates	POD	PPI
Jude Eze	0.86	0.8455
Mathias Daniel	0.82	0.7372
Nwabeke Bright	0.77	0.5863
Alozie Emmanuel	0.71	0.4099
Adamu Zakari	0.65	0.2616

5.3 Numerical Results from Delay Time Model

Assuming the probability density function $f(t)$ of delay time has been chosen as a negative exponential distribution. Let $f(t) = \alpha e^{-\alpha t}$.
Let
T = 24 hours
$f(t)$ = $0.05e^{-0.05t}$
d_b = 0.8 hours
d = 0.3 hours
k = 0.2
Equation 22 is used to calculate the expected downtime while the proportion of breakdown is calculated from Equation 18. Figure 4 shows the corresponding proportion of fault resulting in breakdown with the inspection period with different PPI . At $PPI = 1$, a perfect inspection is sustained (Figure 4).

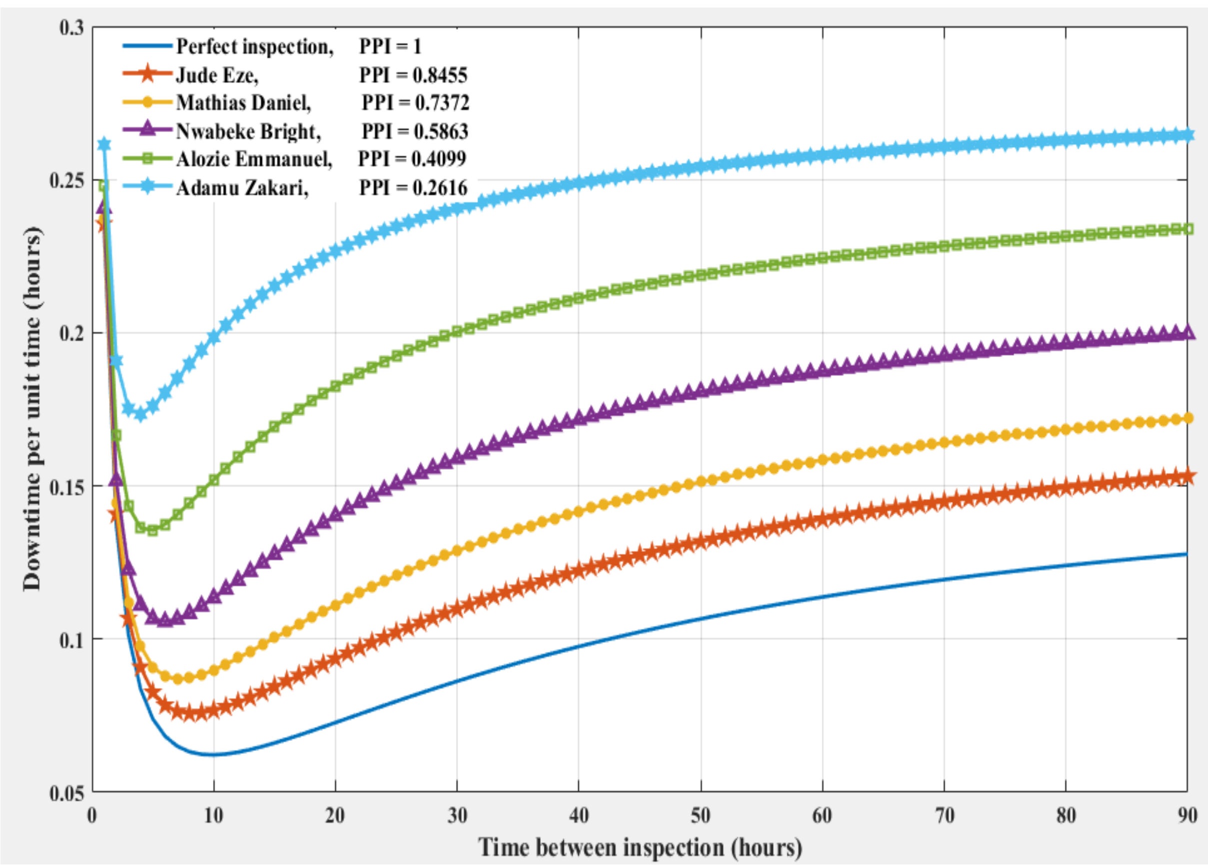

Figure 3. Expected downtime for non-perfect inspection model with different competence.

The proportion of downtime and inspection interval for a given competency rating is given in Table 4.

Table 4. Optimal inspection interval and downtime for competency-based inspection

	POD	PPI	Downtime per unit time (hours)	Optimum Inspection interval (hours)
Perfect inspection	1	1	0.06222	10
Jude Eze	0.86	0.8455	0.07578	8
Mathias Daniel	0.82	0.7372	0.08694	7
Nwabeke Bright	0.77	0.5863	0.1057	6
Alozie Emmanuel	0.71	0.4099	0.1355	5
Adamu Zakari	0.65	0.2616	0.1734	4

5.4 Discussion of Results

From the analysis of the major breakdowns in the plant illustrated in Table 1, man and method are the cuprites. Graphical illustration in Figure 1 reviewed that 95 per cent of the total downtime was due to man and method problems. Both factors are a function of the functional competency of the maintenance team in applying a prescribed maintenance approach. The skill audit template in Table 2 was used to rank the performance of technicians against the required skill set for a defined maintenance system. The performance does during the audit does not completely replicate field performance hence the ASME code was applied as a weed system to ensure that only capable personnel are allowed to carry out maintenance activities. It also helps in mapping out strategic skill upgrades to build the required skill set for a defined maintenance policy and system. The 8/10 test power curve in Figure 3 and Table 3 showed that a poor performance during the evaluation will have the worst impact in the field according to the corresponding PPI.

Using the delay time model, the competency factor was used to estimate the expected downtime from the production system. The result shows the impacts a maintenance technician has in generating downtime from imperfect inspection and repair as illustrated in Figure 4. Table 4 shows that as the competence of a technician drops, there is an increase in the proportion of downtime. For a given cycle of 24 hours, when an inspection is been carried out by Jude Eze with $\text{PPI} = 0.8455$, the expected downtime is $0.07578 \times 24 = 1.8$ hours. When this activity is performed by Adamu Zakari with $\text{PPI} = 0.2616$, the expected downtime is $0.1734 \times 24 = 4.2$ hours. There is about a 56% increase in the proportion of downtime being experienced when the maintenance task is performed by Adamu Zakari. Comparing their corresponding POD scores, Jude Eze only seems to have performed 24% better than Adam Zakari. The small difference in POD score was elaborated by the ASME power curve and the effect was made obvious by the delay time model. This is very important because the skill and knowledge gap can lead to a tremendous increase in downtime in a production environment. Once a production system is set up, the management should focus on the skill of the workforce to sustain the equipment at desired reliability.

6. Conclusion

Analyses of breakdown data without understanding the underlying failure mechanisms will lead to a wrong conclusion and subsequent recurrence of failure. From the study, over 90 per cent of downtime experienced during production was attributed to either man or method. Man and method issues are functions of skill of the workforce. The performance of a technician during evaluation does not exactly represent field performance. The ASME standard performance evaluation was used to determine the corresponding probability of perfect inspection of a technician based on the obtained performance demonstration score. A delay time model was used to account for the effect of competency levels on machine failure, leading to significant downtime. From the case study, as the competency of a technician increases, the probability of missing defects during inspection decreases and also the number of defects leading to breakdown is reduced. The competency of a technician also affects the time to repair a fault and the overall maintenance integrity. To maintain a certain threshold of downtime, it is paramount to focus on the competency of the organizational workforce. This is important in bridging the gap between adopted maintenance techniques and the desired results.

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